

1 **Use of *in situ* and airborne multiangle data to assess**
2 **MODIS- and Landsat-based estimates of surface albedo**

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Abstract –

The quantification of uncertainty of global surface albedo data and products is a critical part of producing complete, physically consistent, and decadal land property data records for studying ecosystem change. A current challenge in validating satellite retrievals of surface albedo is the ability to overcome the spatial scaling errors that can contribute on the order of 20% disagreement between satellite and field-measured values. Here, we present the results from an uncertainty analysis of MODerate Resolution Imaging Spectroradiometer (MODIS) and Landsat albedo retrievals, based on collocated comparisons with tower and airborne multiangular measurements collected at the Atmospheric Radiation Measurement Program's (ARM) Cloud and Radiation Testbed (CART) site during the 2007 Cloud and Land Surface Interaction Campaign (CLASIC'07). Using standard error propagation techniques, airborne measurements obtained by NASA's Cloud Absorption Radiometer (CAR) were used to quantify the uncertainties associated with MODIS and Landsat albedos across a broad range of mixed vegetation and structural types. Initial focus was on evaluating inter-sensor consistency through assessments of temporal stability, as well as examining the overall performance of satellite-derived albedos obtained at all diurnal solar zenith angles. In general, the accuracy of the MODIS and Landsat albedos remained under a 10% margin of error in the SW (0.3 - 5.0 μm) domain. However, results reveal a high degree of variability in the RMSE (root mean square error) and bias of albedos in both the visible (0.3 - 0.7 μm) and near-infrared (0.7 - 5.0 μm) broadband channels; where, in some cases, retrieval uncertainties were found to be in excess of 20%. For the period of CLASIC'07, the primary factors that contributed to uncertainties in the satellite-derived albedo values include: (1) the assumption of temporal stability in the retrieval of 500 m MODIS BRDF values over extended

periods of cloud-contaminated observations; and (2) the assumption of spatial and structural uniformity at the Landsat (30 m) pixel scale.

1. Background

A major goal of international Earth observation efforts is the long term monitoring of terrestrial essential climate variables and the production of consistent land surface radiation parameters for rigorous modeling studies. With the advent of a new generation of multi-sensor data and products for Land science applications, recent efforts have explored the “MODISization” of nadir-looking satellite sensors to obtain high-resolution (30 m) MODIS-driven land surface parameters (Gao et al. 2006; Roy et al. 2008). For example, (Shuai et al. 2011) combined both Landsat reflectance (Masek et al. 2006) and high quality 500 m MODIS BRDF (Bidirectional Reflectance Distribution Function) parameters (Lucht et al. 2000; Schaaf et al. 2002; Schaaf et al. 2008) to retrieve 30 m resolution estimates of surface albedo. By capturing seasonal trends at the characteristic scale of vegetation change (~1 ha), these approaches have the potential to improve our understanding of the climate consequences of global land cover change and ecosystem disturbance (Barnes and Roy 2008; Masek et al. 2008).

The quantification of uncertainty of global surface albedo data and products from both MODIS and Landsat satellites is a critical part of producing complete, physically consistent, global, and decadal land property data records. The MODIS BRDF/albedo standard product, available globally since 2000 at resolutions from 0.5 to 5 km, has been validated to Committee on Earth Observation Satellites (CEOS) Stage 2 (i.e., over a widely distributed set of locations and time periods via several ground-truth and validation efforts). This validation stage is a pre-

requisite for any data product that is used for monitoring change over time (Morisette et al. 2002). The high-quality primary algorithm for the MODIS standard albedo product (MCD43) has also been shown to produce consistent global quantities over a variety of land surface types and snow-covered conditions (Jin et al. 2003a; Jin et al. 2003b; Salomon et al. 2006; Liu et al. 2009; Román et al. 2009; Román et al. 2010; Wang et al. 2011). On the other hand, the combined MODIS/Landsat albedo product (hereby termed ‘Landsat albedo’), which is based on per-class MODIS BRDF shapes based on uniform land cover characteristics, has been shown to provide a more detailed landscape texture and achieve good agreement with in-situ data over a limited number of field stations (Shuai et al. 2011). Additional assessments over a wide range of spatial (from 10s of meters to 5-30 km) and temporal scales (from daily to monthly) are nonetheless required to accurately provide end users with a pixel-specific measure of product uncertainty – both in terms of retrieval quality (e.g. given a limited number of cloud-free satellite observations) and their ability to capture albedo trends under conditions of seasonal and/or rapid surface change.

A current challenge in validating satellite albedo retrievals is the ability to overcome the spatial scaling errors that contribute disagreement between satellite and field-measured values, which can be on the order of 20% (Jin et al. 2003b; Salomon et al. 2006; Liu et al. 2009; Román et al. 2010). Recent studies have acquired measurements atop tall (> 400 m) towers to properly “scale-up” to satellite measurements (Augustine et al. 2005; Román et al. 2009). Other efforts have used high resolution imagery to consider the spatial representativeness of the tower observation footprint to the MODIS pixel (Susaki et al. 2007; Román et al. 2009). While these methods provide a good means by which direct “point-to-pixel” assessments can be performed with

high confidence; they present their own set challenges (e.g., in the United States, instruments atop tall towers cannot be left operating year-round, due to heavy icing and bad weather). On account of the uncertainties arising from direct comparison between sparsely sampled *in situ* measurements and their corresponding satellite products, a formal assessment has yet to be carried out to characterize the ability of the MODIS and Landsat data to capture diurnal trends in albedo across spatially heterogeneous environments. To address these issues, we present the results from an uncertainty quantification of MODIS and Landsat albedo retrievals based on collocated comparisons with tower and airborne measurements. For the airborne datasets, we have employed the retrieval scheme presented in Román et al. (2011a), which follows the operational sequence used to retrieve the MODIS surface reflectance and BRDF/albedo products, based on high-quality multiangular reflectance measurements obtained by NASA's Cloud Absorption Radiometer (CAR) (King et al. 1986; Gatebe et al. 2003). This study focuses on CAR retrievals obtained over the Atmospheric Radiation Measurement Program's (ARM) Cloud and Radiation Testbed (CART) site during the 2007 Cloud and Land Surface Interaction Campaign (CLASIC'07) (Bindlish et al. 2009; Heathman et al. 2009).

2. Albedo retrieval strategy

In this section, we briefly review the albedo retrieval methods used by the MODIS, Landsat, and CAR instruments, and assess the calibration performance of the CAR spectral channels during the period of CLASIC'07. Readers are referred to Sections 2 and 3 in Román et al. (2011a) for detailed descriptions of the CLASIC'07 experiment (including retrieval of CAR and MODIS

BRDF/albedo datasets); and Section 2 in Shuai et al. (2011) for a complete description of the Landsat albedo retrieval strategy.

2.1 Instantaneous albedos from CAR, MODIS, and Landsat

The CAR, MODIS, and Landsat albedo retrieval schemes employ the BRDF kernel model parameters from the reciprocal version of the semiempirical RossThick-LiSparse model (RTLSR) (Wanner et al. 1995; 1997; Lucht et al. 2000):

$$R_{\Lambda}(\Omega_v, \Omega_s) = f_{iso, \Lambda} + f_{vol, \Lambda} K_{vol}(\Omega_v, \Omega_s) + f_{geo, \Lambda} K_{geo}(\Omega_v, \Omega_s) \quad (1)$$

Here, Ω_v and Ω_s are the viewing and solar geometries, which are each defined by zenith and azimuthal angles (θ, ϕ). K_{vol} is the coefficient for the RossThick volume scattering kernel (Ross 1981); K_{geo} is the coefficient of the LiSparse-Reciprocal geometric scattering kernel (Li and Strahler 1992); and $f_{x, \Lambda}$ are the RTLSR kernel weights x in waveband Λ with limits $[\Lambda_{min}, \Lambda_{max}]$ (Wanner et al. 1995; Lucht et al. 2000). The RTLSR kernel weights are then used to compute intrinsic surface albedos (i.e., black sky albedo for direct beam at local solar noon and white sky albedo for isotropic diffuse radiation) (Martonchik et al. 2000; Schaepman-Strub et al. 2006):

$$\begin{aligned} \overline{R}_{\Lambda}(\Omega_i) &= \frac{1}{\pi} \int_0^{2\pi} d\phi_v \int_0^1 R_{\Lambda}(\Omega_v, \Omega_i) \mu_v d\mu_v \\ &= f_{iso\Lambda} + f_{vol\Lambda} \overline{K}_{vol\Lambda}(\Omega_s) + f_{geo\Lambda} \overline{K}_{geo\Lambda}(\Omega_s) \end{aligned} \quad (2)$$

$$\begin{aligned} \overline{\overline{R}}_{\Lambda} &= \frac{1}{\pi} \int_0^{2\pi} d\phi_i \int_0^1 \overline{R}_{\Lambda}(\Omega_i) \mu_i d\mu_i \\ &= f_{iso\Lambda} + f_{vol\Lambda} \overline{\overline{K}}_{vol\Lambda} + f_{geo\Lambda} \overline{\overline{K}}_{geo\Lambda} \end{aligned} \quad (3)$$

where, $R_{\Lambda}(\Omega_v, \Omega_i) = \pi BRDF_{\Lambda}$ (unitless), is the ratio of the surface BRDF to that of a perfect Lambertian reflector, which can be approximated by measurement over some (small) finite angle with diffuse illumination and multiple interaction effects accounted for or assumed zero (Lyapustin and Privette 1999). Subscripts v and i denote the upper ‘viewing’ and ‘incident’ hemispheres. $\bar{R}_{\Lambda}(\Omega_s)$ is the black-sky albedo, $\bar{\bar{R}}_{\Lambda}$ is white-sky albedo, $\bar{K}_{vol}(\Omega_v)$ and $\bar{K}_{geo}(\Omega_v)$ are the directional-hemispherical integrals, and $\bar{\bar{K}}_{vol}(\Omega_v)$ and $\bar{\bar{K}}_{geo}(\Omega_v)$ are the bihemispherical integrals of K_{vol} and K_{geo} . Other terms in Eq. (2) and (3) are:

$$\mu_y = \cos(\theta_y); \quad y = v \text{ or } i \quad (4)$$

To accurately compare these intrinsic quantities against ground-based albedos, the black-sky and white-sky albedos must be combined as a function of solar geometry and atmospheric state to compute instantaneous albedo under assumptions of isotropic diffuse illumination:

$$A_{Iso}(\Omega_s) = \frac{f_{iso\Lambda} + (1 - D_{0\Lambda}) \left[f_{vol\Lambda} \bar{K}_{vol}(\Omega_s) + f_{geo\Lambda} \bar{K}_{geo}(\Omega_s) \right] + D_{0\Lambda} \left[f_{vol\Lambda} \bar{\bar{K}}_{vol}(\Omega_s) + f_{geo\Lambda} \bar{\bar{K}}_{geo}(\Omega_s) \right]}{D_{0\Lambda} \left[f_{vol\Lambda} \bar{\bar{K}}_{vol}(\Omega_s) + f_{geo\Lambda} \bar{\bar{K}}_{geo}(\Omega_s) \right]} \quad (5)$$

where $D_{0\Lambda}$ (unitless) is the proportion of diffuse illumination for an absorbing lower boundary (Lewis and Barnsley 1994; Lucht et al. 2000). The MODIS BRDF shape derived from clear-sky observations can then be used to derive albedo values in all sky conditions (Liu et al. 2009). Most recently, the computation of MODIS instantaneous albedos was updated to account for the effects of multiple scattering and anisotropic diffuse illumination (Román et al. 2010):

$$A_{\Lambda}(\Omega_s) \approx f_{iso\Lambda} + f_{vol\Lambda} \overline{\overline{K''}}_{vol\Lambda}(\Omega_s) + f_{geo\Lambda} \overline{\overline{K''}}_{geo\Lambda}(\Omega_s) \quad (6)$$

$$\overline{\overline{K''}}_{x\Lambda}(\Omega_s) = (1 - D_{0\Lambda}) \overline{K}_x(\Omega_s) + D_{0\Lambda} \overline{\overline{K'}}_{x\Lambda} \quad (7)$$

$$\overline{\overline{K'}}_{x\Lambda} = \frac{1}{\pi} \int_0^{2\pi} d\phi_i \int_0^1 \overline{K}_x(\Omega_i) N_{sky\Lambda}(\Omega_i) \mu_i d\mu_i \quad (8)$$

$$\overline{K}_x(\Omega_v) = \frac{1}{\pi} \int_0^{2\pi} d\phi_i \int_0^1 K_x(\Omega_v, \Omega_i) \mu_i d\mu_i \quad (9)$$

where, $N_{sky\Lambda}(\Omega_i)$ is the normalized sky radiance distribution under an absorbing lower boundary

and $\overline{\overline{K'}}_{x\Lambda}$ is the $N_{sky\Lambda}$ -weighted bihemispherical integral of $K_x(\Omega_v, \Omega_s)$ (where $x = vol$ or geo).

Intrinsic albedo quantities derived from RTLSR BRDF model inversions can then be combined with in-situ estimates of cloud fraction (< 0.6), 550 nm aerosol optical depth (AOD), solar zenith angle (SZA), and $D_{0\Lambda}$ to compute clear-sky instantaneous albedos from MODIS, Landsat, and CAR data.

The kernel-driven models employed by the MODIS and Landsat albedo products are also identified as part of the heritage algorithms used to generate the Visible Infrared Imager Radiometer Suite's (VIIRS) Land Environmental Data Records (EDRs); which aim to ensure continuity for AVHRR and MODIS observations by providing high temporal resolution and wide area coverage (Lee et al. 2010). The VIIRS Land EDRs are currently being evaluated by NASA and NOAA to assess their suitability for operational weather forecasting and long-term climate monitoring applications (Román et al. 2011b).

2.2 Narrowband to Broadband Conversion

Since field-measured albedos are commonly measured as broadband quantities, an equivalent set of broadband albedos for MODIS and Landsat were generated for the UV-Visible (0.3 - 0.7 μm), NIR (0.7 - 5.0 μm), and the entire spectrum of solar radiation ([SW] 0.3 - 5.0 μm), based on empirical relations between ground-based albedo measurements and satellite observations – *cf.*, Eqs. (11) and (15) in Liang (2001). Broadband albedos were also derived for CAR measurements by calculating the ratio of broadband upwelling radiative flux to broadband downwelling flux (Liang 2001; Liang et al. 2003):

$$F(\Omega_s) = \frac{\int_{\Lambda_{\min}}^{\Lambda_{\max}} A(\Omega_s) D(\Omega_s, \Lambda) d\Lambda}{\int_{\Lambda_{\min}}^{\Lambda_{\max}} D(\Omega_s, \Lambda) d\Lambda} = \sum_i c_i A(\Omega_s, \Lambda_i) \quad (10)$$

Then, CAR narrowband-to-broadband spectral albedo coefficients, c_i , were generated for each spectral band by determining the downward fluxes (i.e. direct and diffuse) using an library of 30 reflectance spectra of representative land covers in the ARM Southern Great Plains (SGP) region (Trishenko et al. 2003):

$$A_{\text{short}} = 0.160\alpha_1 + 0.291\alpha_2 + 0.243\alpha_3 + 0.116\alpha_4 + 0.112\alpha_5 + 0.081\alpha_7 - 0.0015 \quad (11)$$

$$A_{\text{NIR}} = 0.039\alpha_1 + 0.504\alpha_2 - 0.071\alpha_3 + 0.105\alpha_4 + 0.252\alpha_5 + 0.069\alpha_6 + 0.101\alpha_7 \quad (12)$$

$$A_{\text{visible}} = 0.331\alpha_1 + 0.424\alpha_3 + 0.246\alpha_4 \quad (13)$$

The upward fluxes were directly obtained from the library of 30 SGP reflectance spectra; while the downward fluxes were obtained by performing multiple MODTRAN@5.1 (Berk et al. 2004) runs for a broad range of snow-free conditions (i.e., 21 atmospheric visibility values for different aerosol loadings, 2 atmospheric profiles, and solar zenith angles ranging from 0° - 80° with the increment of 1°).

2.3 CAR instrument performance during CLASIC'07

During the CLASIC'07 experiment, radiometric calibration of the CAR spectral channels was made at the NASA Goddard Space Flight Center Radiometric Calibration Facility (GSFC-RCF) (Butler and Barnes 2003). A description of the calibration scheme, using a series of integrating spheres with diameters of 1.83 m, 1.22 m, and 0.51 m, covering all of the CAR's spectral channels, can be found in Gatebe et al. (2007). The conversion from Digital Numbers (DNs) to Level 1 at-sensor radiances is determined from the instrument's response for at least two known radiance levels and then determining the instrument gain (slope) and offset (intercept) for each wavelength across the sensor band pass. The estimated errors associated with this radiometric conversion vary from $\pm 1\%$ to $\pm 3\%$ for all spectral channels (Gatebe et al. 2003; Gatebe et al. 2007). Radiometric calibration was performed prior to and after CLASIC'07. In the past, to determine a suitable calibration for a given flight during the experiment, a linear change between the preflight and postflight calibration was assumed as a function of only the number of flights flown during an entire campaign. For the CLASIC'07 experiment, however, both the pre- and post-calibration coefficients were averaged. This was found to be representative of each flight scenario, and made it easier to account for uncertainties related to calibration, stability, and wa-

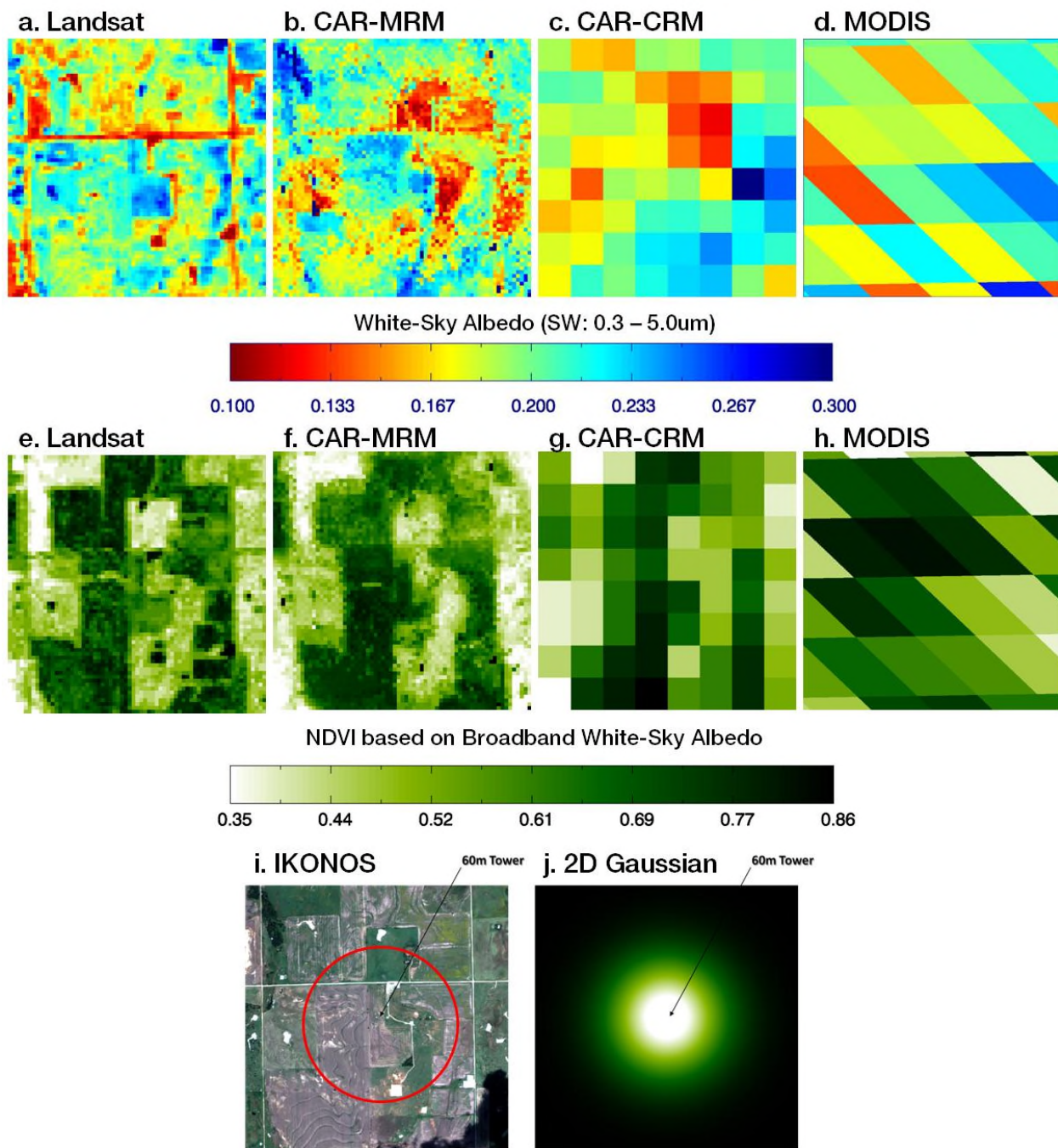
velength errors. We note that the calibration ratios, postflight-to-preflight, varied between 0.9691 (at $\Lambda = 0.472 \mu\text{m}$) and 1.1845 (at $\Lambda = 0.340 \mu\text{m}$).

Table 1. Remotely-sensed albedo retrieval scenarios obtained during CLASIC’07 for MODIS, Landsat, CAR in medium resolution mode (MRM), and CAR in coarse resolution mode (CRM).

Instrument	GIFOV (m)	Scale (m)	BRDF Retrieval Period (DOY)	Albedo Reconstruction Period (DOY)
MODIS Terra/Aqua	436 – 1686	500	145-193	153-155; 159-190
Landsat TM	30	30	153-168	153-155
CAR-MRM	15 – 45	30	175	153-155
CAR-CRM	90 - 360	250	175	159-190

3. Retrieval scenarios during CLASIC’07

Table 1 provides a summary of the individual BRDF retrieval and albedo reconstruction periods for CAR, MODIS, and Landsat. Note that the retrieval scenarios varied by sensor. For instance, Landsat albedos were reconstructed for a short time period (Day of the year, DOY 153-155) to better represent the per-class albedo-to-nadir-reflectance (A/N) ratios derived from the concurrent MODIS acquisition period. Conversely, the CAR albedos are based on two different modes: a Medium Resolution Mode (CAR-MRM) to match the scale of Landsat data; and a Coarse Resolution Mode (CAR-CRM) to match the scale of MODIS data (*cf.*, Fig. 9 in Román et al. 2011a). The CAR measurements are based on CLASIC Flight #1928 (DOY 175, 2007). Accordingly, a longer measurement period was also examined (i.e., DOY 159-190) to evaluate the ability of the CAR and MODIS data to represent the landscape conditions surrounding the entire CLASIC’07 period.



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215 **Fig. 1. (a. – h.) 2 km x 2 km subsets illustrating retrievals of white-sky albedo (WSA) and broad-**
 216 **band NDVI. The Broadband NDVI values are based on the UV-VIS and NIR portions of the solar**
 217 **spectrum: $NDVI = (WSA_{NIR} - WSA_{VIS}) / (WSA_{NIR} + WSA_{VIS})$. (i.) IKONOS true-color scene, re-**
 218 **trieved on 1 July 2007, denotes the ~960 m ground footprint as seen by the downward-facing pyra-**
 219 **nometer atop the CART site's 60 m radiation tower. (j.) Spatially-integrated albedos for CAR,**
 220 **Landsat, and MODIS, were computed based on a 2D Gaussian filter representing the tower foot-**
 221 **print.**

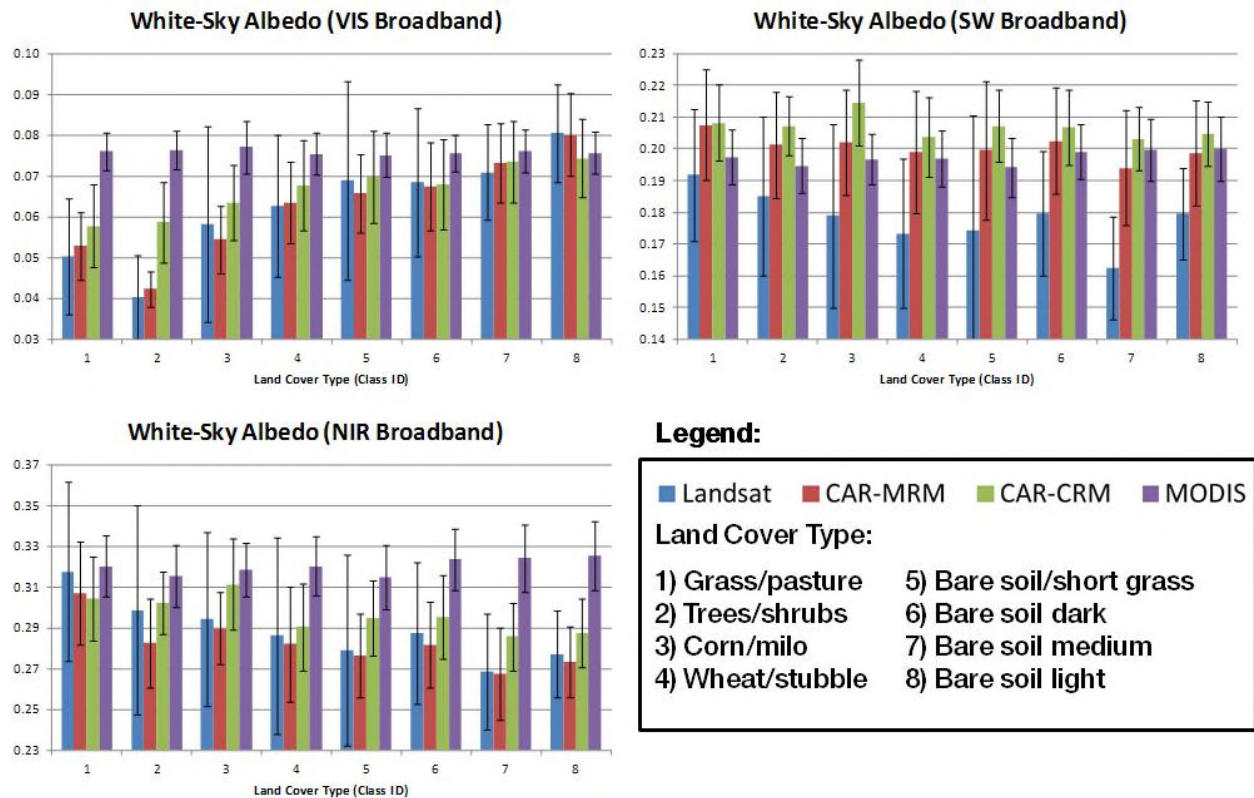


Fig. 2. Comparisons of intrinsic white-sky albedos derived from Landsat, CAR, and MODIS data shown for individual land cover types present across the ARM CART during CLASIC'07. Results were partitioned into broadband albedos based on the UV-Visible (0.3 - 0.7 μm), NIR (0.7 - 5.0 μm), and the entire spectrum of solar radiation ([SW] 0.3 - 5.0 μm).

Fig. 1 illustrates several 2 km x 2 km subsets based on CAR, MODIS, and Landsat retrievals of SW white-sky albedo (WSA) (Fig. 1a –d), broadband NDVI (Fig. 1e –h), as well as a true-color IKONOS scene retrieved on 1 July 2007 (Fig. 1i). The red circle over the IKONOS scene denotes the ~960 m ground diameter footprint as seen by the downward-facing pyranometer atop the CART site's 60 m radiation tower. Throughout the analysis stage in Section 4, a Gaussian filter was applied to the CAR, MODIS, and Landsat data to compute spatially-integrated albedos that represented the tower's ground-projected instantaneous field of view (GIFOV) (Fig. 1j).

In order to quantify the temporal consistency of albedo retrievals during the period of CLASIC'07, estimates of broadband NDVI were generated for each sensor (e.g. Fig. 1e – h). NDVI estimates based on broadband white-sky albedos were used to minimize the influence of variable sun-target-sensor configurations when estimating measurement differences and changes in vegetation conditions (Huete et al. 2002). Results in Fig. 1 show how areas north of the CART site and the winter wheat fields just east and west of the site, appear to be more vegetated during the Landsat overpass period (DOY 154). However, the overall change in NDVI was relatively small throughout the CLASIC'07 period (DOY 153-190) (i.e., ~5.7% for the entire study area and ~8.0% for the area within the CART tower footprint).

The WSA results in Fig. 1a – 1d show some similarities between the CAR-CRM and MODIS WSA data, as well as some differences between the finer resolution Landsat and CAR-MRM albedos. In particular, the Landsat albedos (Fig. 1a) could resolve fine-scale spatial features across the CART site (e.g., small buildings and dirt roads); but were also characterized by higher 'within-biome' variability. This is demonstrated in Fig. 2, which illustrates the overall mean and standard deviations in white-sky albedo based on individual estimates obtained for each representative land cover class identified across the CART site. The ancillary land cover data is based on field surveys, vegetation measurements, and surface characterizations performed during CLASIC'07 (Román et al. 2011a). Unlike the MODIS and CAR intrinsic albedos, which are driven by the anisotropy of each pixel, the Landsat retrieval scheme is based on per-class MODIS BRDF shapes based on uniform land cover characteristics. This resulted in WSA retrievals of varying magnitudes, particularly across mixed cover types (e.g., bare soil mixed with short

grass). This is in contrast to the relatively lower within-biome variability seen in the CAR and MODIS white-sky albedos across all land cover classes and broadband channels.

Additional quality assurance (QA) checks were performed to assess the consistency of each retrieval scheme. For this study, both the Landsat and MODIS intrinsic albedos were based on gap-free, quality-enhanced BRDF retrievals that rely on spatial and temporal fitting techniques to compensate for missing data and provide an estimate of the surface reflectance anisotropy for situations under cloud-contaminated conditions (Zhang 2008). For the period surrounding the Landsat date of acquisition, the MODIS retrievals were all based on high-quality “majority” full inversion values. Conversely, the data acquisition period surrounding the CAR measurements (DOY 175) was impacted by changing weather conditions (e.g., clouds and rainfall events). These weather conditions resulted in the majority of MODIS retrievals to be based on lower-quality temporally-fitted pixels; particularly, throughout DOY 161-190. Consequently, MODIS retrievals provided a close, but not exact, representation of the surface conditions surrounding the CAR measurements during the CLASIC’07 experiment. For an in-depth look at the MODIS and CAR quality assurance assessment, readers are referred to Section 3 in Román et al., (2011a), where QA summaries based on data from CLASIC Flight #1928 are available.

Understanding the above mentioned differences in BRDF/albedo retrieval strategies and data acquisition periods, it is important to note that the ground-based observations obtained at the CART site provide a consistent reference source for all albedo reconstructions (albeit for a small area the size of a few MODIS pixels) (*cf.*, Section 4). Furthermore, as we will demonstrate in

Section 5, the CAR data can help reduce the propagation of measurement uncertainty and error when evaluating the satellite-based retrieval schemes at the individual pixel level.

4. Comparisons to tower-based measurements

We now examine the diurnal performance of instantaneous albedos derived from CAR, MODIS, and Landsat, based on comparisons against available in situ observations acquired during CLASIC'07. Measurements from a downward-facing pyranometer installed on a 60 m radiation tower at the CART site collected albedo and radiation fluxes in the shortwave (SW) (0.3- 2.8 μm) waveband (Fig.1i). Two additional instruments, a normal incidence pyrhelimeter mounted on an automatic sun tracker and a shaded pyranometer riding on top of the sun tracker, measured direct and diffuse solar radiation incident upon the field station (*cf.*, Fig. 3 in Román et al., 2011a). Estimates of cloud fraction and aerosol optical depth, as viewed from a skyward-looking pyranometer and an AERONET sunphotometer (Holben et al. 2001), were also collected. This measurement scheme follows a strict set of guidelines as established by the International Baseline Surface Radiation Network (BSRN) (McArthur 2005; WMO 2006). BSRN measurement protocols are recognized as the international standard for in situ albedo data, with a review process that includes additional quality assurance (QA) checks (e.g. standard units, naming conventions, and reporting intervals) to maintain consistency within the larger network-wide BSRN database (Schaaf et al. 2009).

Following the albedo reconstruction periods described in Table 1, results in Figs. 3 and 4 show comparisons between the tower-based albedos and instantaneous albedos derived from CAR, MODIS, and Landsat data. Measurements of aerosol optical depth (AOD) at 550 nm are

297 also plotted in Fig. 4 (right-axis); while AOD measurements recorded during DOY 153-155 (Fig.
298 3) remained low and constant throughout this period (i.e., $AOD = 0.1676 \pm 0.0590$). Results
299 show the usual “U-shaped” diurnal trend in instantaneous albedo that reaches a minimum value
300 around local solar noon time. In general, the CAR and MODIS albedos met the absolute accura-
301 cy requirement of 0.02 units (i.e., within 10% of surface measured values) for instantaneous SW
302 albedos at $SZA < 45^\circ$ (i.e., between 10.00 and 16.00 local time); with the CAR-CRM albedo data
303 also performing well at $SZA > 45^\circ$ (i.e., before 10.00 and after 16.00 local time). Conversely,
304 both MODIS and Landsat consistently underestimated the tower albedos at $SZA > 45^\circ$. The sta-
305 tistical results in Tables 2 and 3 show similar negative trends in the biases derived from MODIS
306 and Landsat albedos. Finally, CAR and MODIS retrievals based on the full expression of instan-
307 taneous albedo (Eq. 6) showed slight improvements by ~ 0.0065 absolute units over the isotropic
308 albedo formulation (Eq. 5). As seen for several dates in Fig. 4, the full expression results for
309 MODIS and CAR are much closer to the daily albedo maxima at $SZA = 75^\circ$.

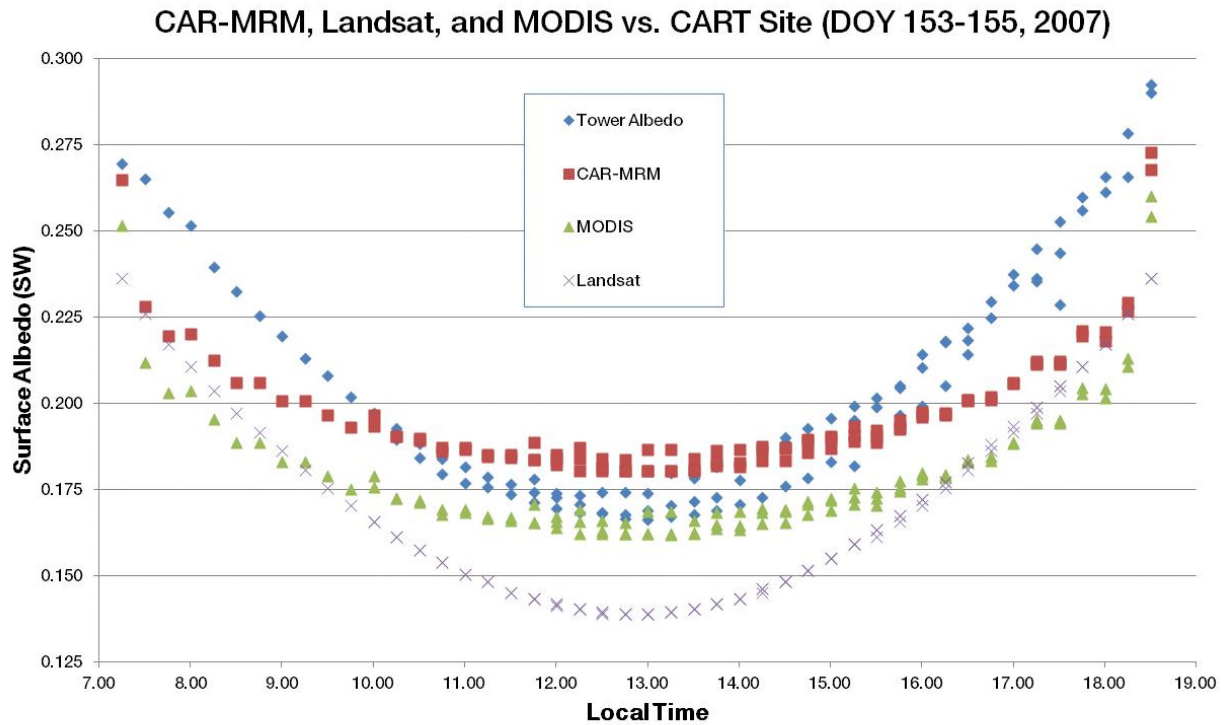


Fig. 3. Comparisons between instantaneous retrievals of surface albedo (15-min intervals) derived from CAR-MRM (red squares), MODIS (green triangles), Landsat ('X' marks), and tower-based measurements (blue diamonds) acquired at the CART site throughout a 3-day period surrounding the Landsat overpass date (DOY 154, 2007).

Table 2. Accuracy^a, (absolute bias) and uncertainty^b (RMS of absolute error or RMSE) values resulting from comparisons between ground-based (CART), airborne (CAR-MRM), and satellite-derived (MODIS and Landsat) albedos as illustrated in Fig. 3. The total sample size (n) for two solar zenith angle (SZA) ranges is shown.

	10° ≤ SZA ≤ 45° (n = 69)			45° ≤ SZA ≤ 75° (n = 34)		
DOY 153-155,2007	CAR-MRM	MODIS	Landsat	CAR-CRM	MODIS	Landsat
Accuracy (Bias)	0.0044	-0.0136	-0.0324	-0.0266	-0.0433	-0.0401
Uncertainty (RMSE)	0.0090	0.0157	0.0327	0.0287	0.0447	0.0407

^aAccuracy = arithmetic mean (Sensor – Tower)

^bUncertainty: RMS of absolute error = $\sqrt{\text{arithmetic mean (Sensor - Tower)}^2}$

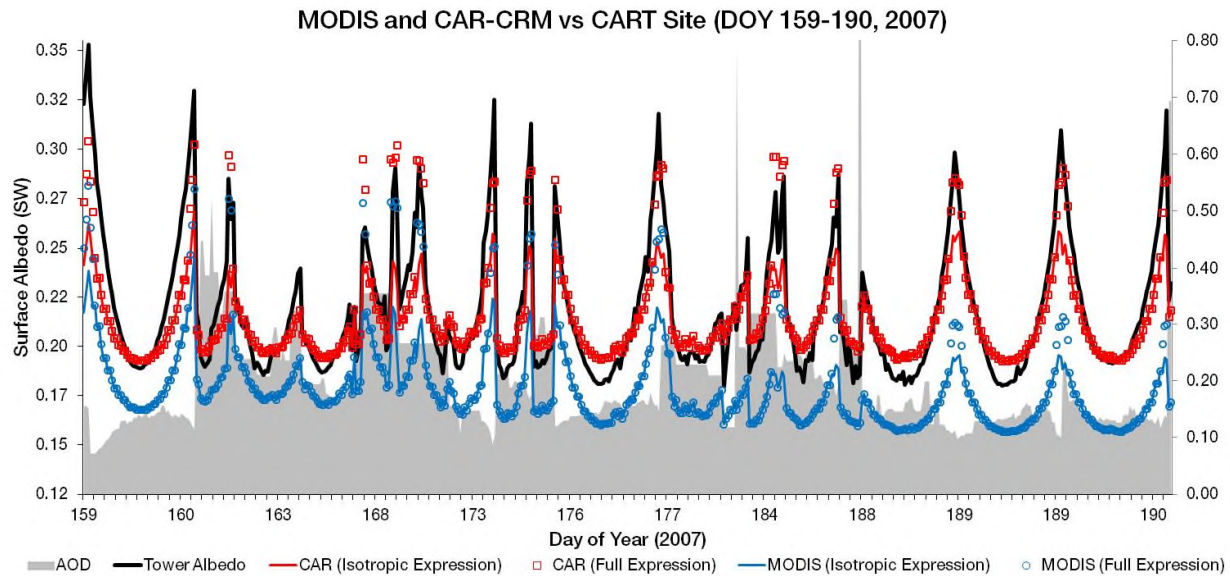


Fig. 4. Comparisons between instantaneous albedos (30-min intervals) derived from CAR-CRM and MODIS (using both isotropic and full expressions), and tower-based measurements acquired at the CART site throughout a 32-day period surrounding CLASIC Flight #1928 (DOY 175, 2007).

Table 3. Accuracy and uncertainty values resulting from a 32-day comparison between ground-based (CART), airborne (CAR-CRM), and satellite-derived (MODIS) albedos as illustrated in Fig. 4. Setup is the same as Table 2.

	$10^{\circ} \leq \text{SZA} \leq 45^{\circ}$ (n = 289)		$45^{\circ} \leq \text{SZA} \leq 75^{\circ}$ (n = 193)	
DOY 159-190,2007	CAR-CRM	MODIS	CAR-CRM	MODIS
Accuracy (Bias)	0.0042	-0.0286	-0.0096	-0.0495
Uncertainty (RMSE)	0.0082	0.0296	0.0184	0.0526

5. Regional assessment of MODIS and Landsat albedos

In the previous section, CAR retrievals were shown to be of sufficient accuracy and consistency to reproduce the diurnal variations in albedo across the CART site throughout the entire period of CLASIC'07. Using the CAR-MRM and CAR-CRM instantaneous albedos as “ground-truth”, we now employ standard error propagation techniques (Heuvelink 1998) to quantify the uncertainties associated with MODIS and Landsat instantaneous albedos over a mixture of landscapes extending beyond the tower observation footprint at the CART site.

Assuming that the error propagation terms in Eqs. (14 -15) are uncorrelated, the Root-Sum-of-Squares Error (RSSE) can be used to provide estimates of retrieval uncertainty (absolute RMSE) and bias, both in an absolute and temporal sense:

$$RSSE_{MODIS} = \sqrt{Err(\hat{\theta}_{tower \rightarrow CAR-CRM})^2 + Err(\hat{\theta}_{CAR-CRM \rightarrow MODIS})^2} \quad (14)$$

$$RSSE_{Landsat} = \sqrt{Err(\hat{\theta}_{tower \rightarrow CAR-MRM})^2 + Err(\hat{\theta}_{CAR-MRM \rightarrow Landsat})^2} \quad (15)$$

where $Err(\hat{\theta}_x)$ denotes the “in-situ to satellite” error propagation chain based on two component factors. CAR BRDF/albedo retrievals were then matched to the resolution of MODIS and Landsat to minimize errors due to sub-grid scale mismatch and the effects of land surface heterogeneity. Additional checks were also performed to limit the sampling of CAR pixels to the highest quality “majority” full BRDF inversion values. For CLASIC’07, this resulted in 789 individual samples, each of which was tested following the same albedo reconstruction periods presented in Section 3.

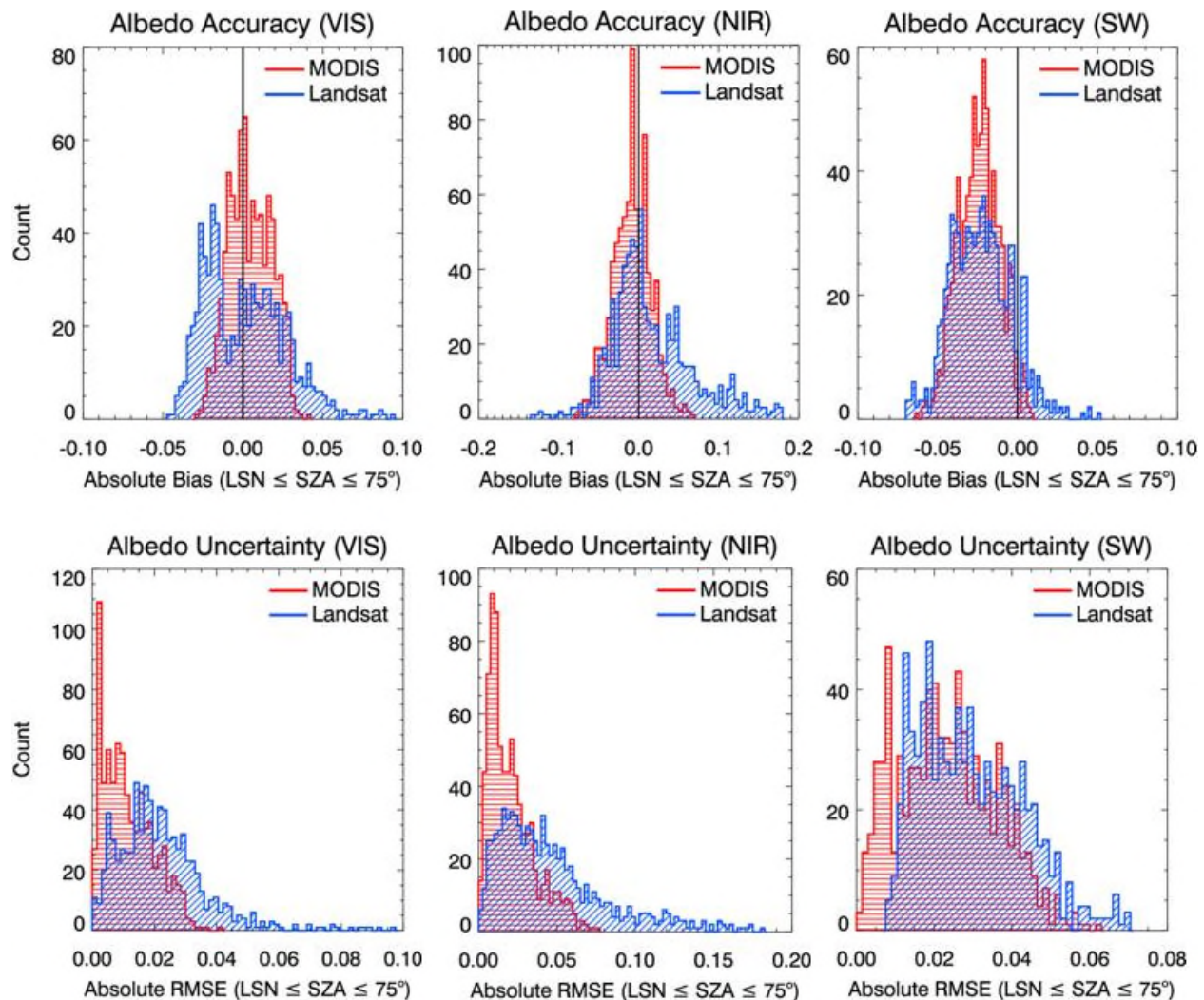


Fig. 5. Distribution of absolute bias (accuracy) and RMSE (uncertainty) for MODIS and Landsat instantaneous albedos at UV-Visible, NIR, and SW broadband channels for the CLASIC'07 period over the CART site.

Results were examined by comparing the distribution of biases and RMSEs resulting from MODIS and Landsat instantaneous albedos at $LSN \leq SZA \leq 75^\circ$. The histogram plots in Fig. 5 show a persistent negative bias (-0.03) in SW instantaneous albedos, corresponding to the biases recorded for MODIS and Landsat in earlier assessments (*cf.*, results in Tables 2 and 3). Likewise, for the NIR broadband, roughly 19% of Landsat retrievals showed positive biases above the standard accuracy limit of ± 0.072 units. In the VIS broadband, a small fraction of MODIS (23%)

and a large fraction of Landsat retrievals (57%) were also above the standard accuracy limit of ± 0.018 units. To understand the causes of such differences, a collection of ternary diagrams were created to determine how each sensor performed at the individual pixel level. The diagrams in Fig. 6 have been arranged such that retrievals located near the top originate from landscapes dominated by non-photosynthetic (or 'brown') vegetation (i.e., combined land cover (LC) classes 1, 4, and 5 in Fig. 2). Conversely, retrievals located near the bottom-left correspond to areas dominated by bare soils (i.e., combined LC classes 6, 7, and 8 in Fig. 2), and retrievals located near the bottom-right correspond to areas dominated by green vegetation (i.e., combined LC classes 2, and 3 in Fig. 2). Thus, the closer the satellite retrievals are to the center portions of the ternary diagrams, the more mixed is the landscape.

Results reveal a large degree of variability in the RMSE and bias estimates of MODIS and Landsat albedos, both between fractional cover types and across broadband channels. In particular, the MODIS NIR values remained stable across most landscape regimes, with only a few samples identified above the 20% margin of error for snow-free conditions (Fig. 6e). A synoptic analysis of the ternary diagrams also suggests that the uncertainties in the NIR broadband are more likely to propagate into the SW domain (Figs. 6i–6l). The MODIS VIS broadband also appeared to capture bare-soil albedo variability (i.e., wet vs. dry areas) with high accuracy (-0.008); but the biases were moderately larger over mixed landscapes ($+0.012$) and regions dominated by non-photosynthetic vegetation ($+0.019$) (Fig. 6a). Conversely, the Landsat albedos were less stable in the NIR, with positive biases ($+0.05$) dominating over mixed landscapes (Fig. 6f). The same error patterns were seen in the VIS broadband, where more than half of Landsat retrievals

were above the 20% margin of error (Fig. 6d). The latter resulted from varying magnitudes across mixed cover types and regions dominated by bare soils (Fig. 6b).

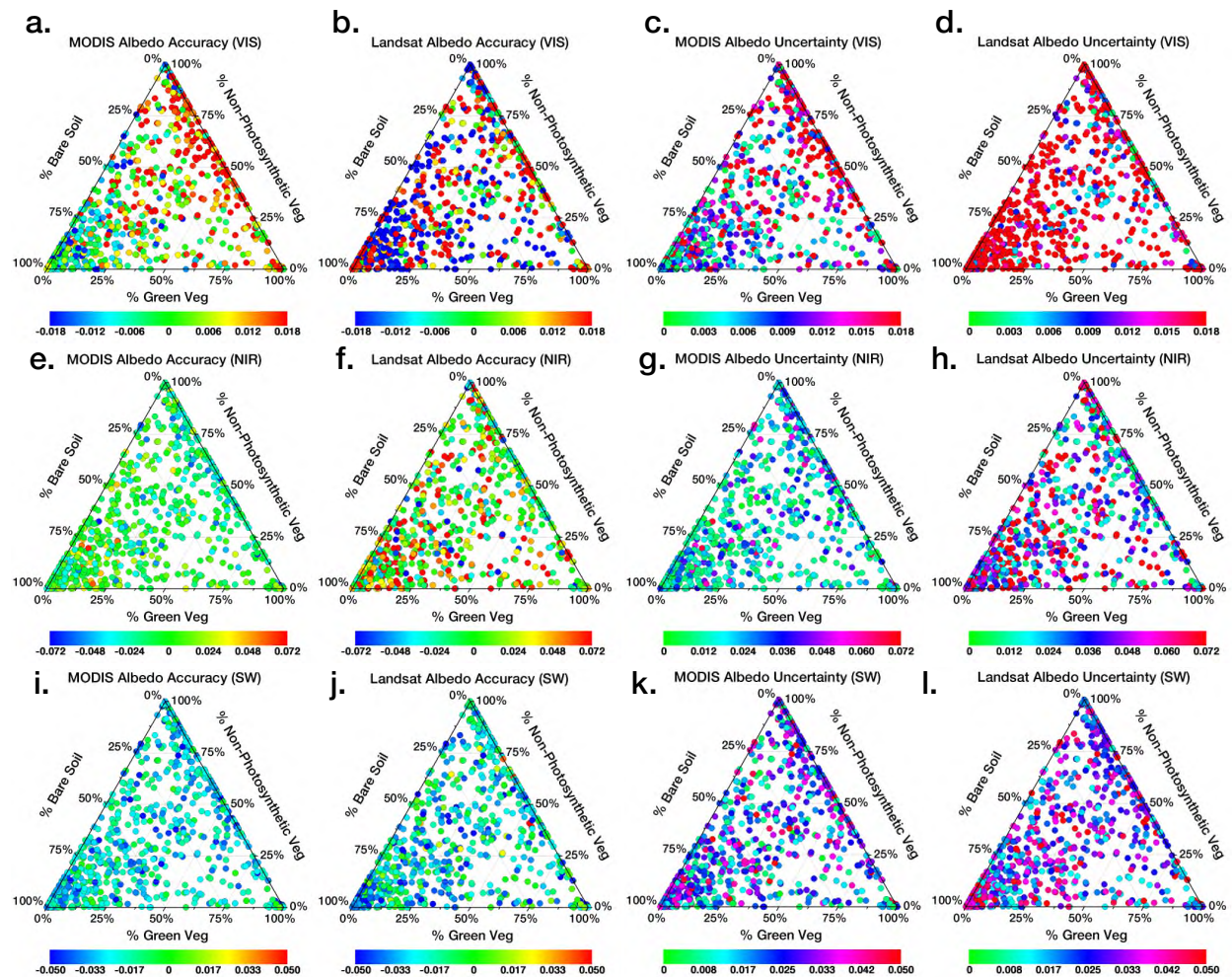


Fig. 6. Ternary diagrams illustrating the pixel-specific accuracy (absolute bias) and uncertainty (absolute RMSE) of MODIS and Landsat instantaneous albedos ($LSN \leq SZA \leq 75$) at UV-Visible (a. – d.), NIR (e. – d.), and SW (i. – l.) broadband channels for the CLASIC’07 period over the CART site. For each color scale, green denotes values where the bias or RMSE = 0. For the accuracy diagrams, the lower (blue) and upper (red) limits correspond to retrievals that are at or above a 20% margin of error (i.e., relative to in-situ measurements obtained under snow-free conditions). For the uncertainty diagrams, the upper (red) limit denotes the same (20%) margin of error.

For the period of CLASIC’07, there were two major factors that contributed to the uncertainties in the satellite-derived albedo values. First, it is unlikely that the assumption of temporal

397 stability in the retrieval of 500 m MODIS BRDFs could hold together throughout the extended
398 periods of cloud-contaminated observations experienced during CLASIC'07. Daily records from
399 land cover surveys performed on DOY 166-173 over landscapes surrounding the CART site con-
400 firm that several parcels of corn, milo, and winter-wheat were being harvested before full maturi-
401 ty due to floods experienced along the Salt Fork Arkansas River (located 5 km north of the
402 CART site). A visual inspection of the 2.4 m IKONOS scene acquired on 1 July (Fig. 1i) also
403 confirms these events. Thus, it is likely that the negative (-0.03) biases in MODIS SW albedos
404 are caused by the use of temporally-fitted BRDF shapes that are driven by “majority” full inver-
405 sion values obtained prior to the early harvesting period (i.e., DOY 145-153, 2007). This may
406 explain why the uncertainties of MODIS VIS albedos were predominantly above the 20% mar-
407 gin of error over areas dominated by senescent winter-wheat fields; but remained well under the
408 10% margin of error over areas dominated by bare soils.

409 For the Landsat albedos, another major source of uncertainty is the assumption of spatial and
410 structural uniformity at the Landsat (30 m) pixel scale. In the Landsat albedo retrieval algorithm,
411 “pure” land cover clusters are identified on a regional basis and then associated with MODIS
412 anisotropy information through scaling of 500 m BRDF retrievals to 30 m resolution. However,
413 recent assessments of the CLASIC Flight #1928 dataset have indicated that the use of dominant
414 archetypal BRDF shapes to describe the anisotropy of heterogeneous pixels may lead to errors on
415 the order of 0.5% – 6.5% in the retrieved directional reflectance values (*cf.*, Fig.10 in Román et
416 al., 2011a). This will particularly affect retrievals where heterogeneous conditions are being
417 lumped into a single land cover class (e.g., bare soil areas not being properly partitioned into dry,
418 wet, and damp conditions.) As discussed in Shuai et al., (2011) these situations can be addressed

by breaking “pure” land cover clusters into multiple sub-clusters representing different surface conditions.

6. Conclusions and future recommendations

The diurnal performance of the MODIS and Landsat albedo algorithms (Schaaf et al. 2002; Shuai et al. 2011) is evaluated using field and airborne measurements coincident with Landsat TM and multi-date MODIS Terra/Aqua overpasses. For the broad range of mixed vegetation and structural types examined during the period of CLASIC’07, the overall accuracy of MODIS and Landsat SW (0.3 -5.0 μm) albedos is within a 10% margin of error and shows an increasing negative bias (-0.03) and increased RMSE (0.05) as zenith angle increases compared with the in-situ measurements. Results also reveal a high degree of variability in the RMSE and bias of MODIS and Landsat albedos in both the visible (0.3 - 0.7 μm) and near-infrared (0.7 - 5.0 μm) broadband channels. However, we note that the lack of high-quality “majority” 500m MODIS BRDF pixels through the experiment hindered the band-dependent quality controls, as outliers were more difficult to identify. This was particularly the case in the VIS broadband, where cloud contamination and mixed-pixel contamination are highly likely. Despite such limitations, results obtained indicate that MODIS VIS/NIR albedos are able to capture bare-soil albedo variability (i.e., wet vs. dry areas) with high accuracy (-0.008).

While recent product development, intercomparison, and validation efforts have focused almost entirely on the retrieval of surface albedos for a single SW broadband value, it is important to note that most numerical prediction models (and global climate and biogeochemical models) currently in use call for surface energy fluxes and some biophysical variables to be calculated

separately by disentangling broadband albedos into fractional areas of bare soil and vegetation (Noilhan and Mahfouf 1996; Koster et al. 2000; Ek et al. 2003; Kaptué et al. 2010). It is therefore important to continue examining how the accuracies of global albedo products are holding up in these spectral regimes. Likewise, the uncertainties that may impact satellite-inferred albedo trends must be assessed and expressed in terms of a reference sensor that can overcome the foretold errors due to sub-grid scale mismatch and the effects of land surface heterogeneity. It is thus critical that continuous, long-term tower measurements of surface albedo and radiation fluxes be done in concert with intensive airborne measurement campaigns that can focus on addressing sources of uncertainties at both plot-level (< 90 m) to landscape-level (> 90 m) scales.

It is clear that spatial scale of signal aggregation is very important in the retrieval of meaningful surface radiation properties of vegetated surfaces from multiangle and pseudo-multiangular remote sensing data. This is forcing experimenters to develop new measurement and validation protocols for surface BRDF and albedo estimation (Walthall et al. 2000; Schaaf et al. 2009). Ongoing studies combining airborne multiangular measurements from CAR with measurements of terrestrial biomass and ecosystem structure, e.g., NASA's L-band Digital Beam-forming Synthetic Aperture Radar (DBSAR) (Rincon et al. 2011) and the Slope Imaging Multipolarization Photon-counting Lidar (SIMPL) (Dabney et al. 2010), will provide us with new insights to issues of landscape-level variability and the opportunity to continue examining mixed pixels from both medium and coarse scale resolution systems.

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